THERMAL MACHINES

The development of machines has been one of the key factors in the establishment of modern developed societies.

In this teaching unit we want you to understand the role that machines have played throughout history: first as simple **human energy savers**; then as devices able to **take advantage of natural forces like wind or water**; finally as sophisticated machinery able to **convert some forms of energy into others**, always for our benefit. You will also be able to understand how Nature imposes some limitations on these transformations.

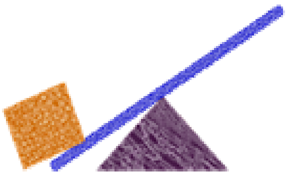
Click next to see our objectives in detail.

Objectives of the teaching unit

- To understand the concept of a simple machine as an instrument which saves effort but not work.
- To understand the way in which energy from wind or water is converted into the mechanical energy of a circular movement.
- To assimilate the equivalence between mechanical energy and heat.
- To formulate the first and second law of thermodynamics in a simple way.
- To learn to use the mathematical formulae for these laws to make simple predictions about the working of engines and machines.

1.1 A simple machine

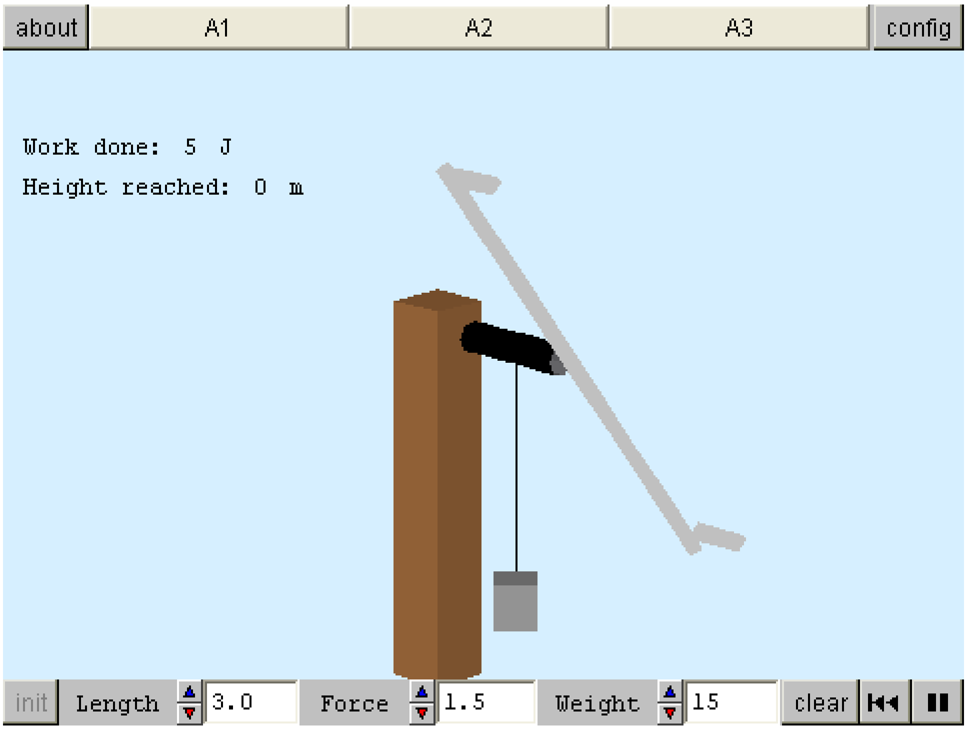
Machines are devices aimed at reducing the effort necessary to carry out arduous tasks. In the illustration you can see a lever, the simplest machine found in history. It enables us to lift a heavy weight with a relatively small force.



In this machine we can already see a very generalized characteristic in the world of machines: the use of the characteristics of circular movement (the whole lever turns around the fulcrum).

In the following visual we will study another simple machine to define the usefulness of this type of device and to understand its limitations.

A pulley worked by a crank. See activity A.1

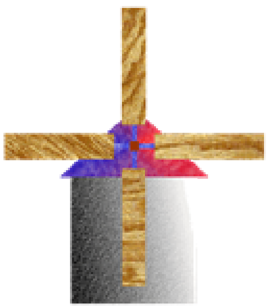


A1: The machine cannot lift the weight initially because it needs a greater torque. Can you remember the value of this magnitude? Increase the length of the crank until the movement is possible. Click on play and note the aumount of work done. Click on init. Repeat the experiment, but this time increase the force. What can you see regarding the work done either way?

A2: A section of the axis has a radius of 0.25 m. Find the smallest value of length of the crank and force that allow the weight to be lifted by trial and error. Calculate the torque of the force in relation to the axis and the torque of the weight in relation to the axis. What can you see? Why is this machine useful?

A3: Note the work done with different combinations of force and length for different values of the weight. Draw a table in your notebook with the different values, writing down the work done in each case. For each value of the weight, what can you see regarding the work carried out? Does this machine save energy if we compare it with the amount of energy that we would need to lift the weight with our own hands, without any help?

1.2 An energy saving machine

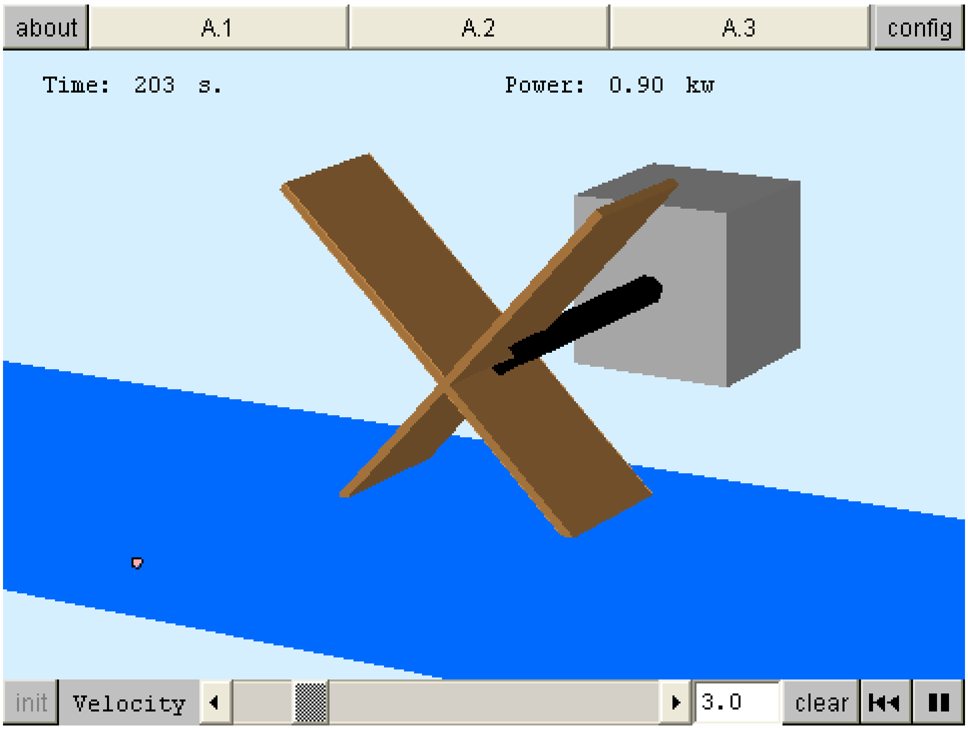


We have already seen that **simple machines reduce the force necessary to carry out a task, but not the work we need to do to complete it.** Throughout history we have often used the work of animals to replace human work.

This, for example is the case of the noria or water wheel, traditionally moved by a mule or an ox.

A better alternative consists of using the energy from natural phenomena to transform it into useful mechanical work. You won't find it hard to identify what type of energy transformation can be carried out by the windmill in the illustration.

In the following visual you can study in detail another example of the transformation of a natural energy into mechanical work.



A1: Turn on the machine with the velocity of the water set to a value greater than zero. Explain what transformation of energy makes the turbine rotate. Calculate the work done in a minute when the water is set to maximum speed.

A2: Write down the power reached for different values of the velocity. Are velocity and power proportional? How about velocity squared and power? Calculate the constant proportion. Reflect about the cause of this relation.

A3: Do the following calculation and then check it with the visual: What must the velocity of the water be if the machine is to carry out 100,000 joules of work in 10 seconds?

1.3 Conclusions about the concept of a machine

Machines are tools designed to reduce human effort in any transformation task. We should emphasize three simple ideas:

Simple machines (levers, cranks, pulleys...) **reduce the force** necessary to carry out a task. Their common idea is that the moment of a force, able to generate a rotation, depends on the force applied and the distance from the axis of rotation. By increasing this distance it is possible to achieve large moments with little effort.

Simple machines save effort but not work. If we want to save mechanical work, the way to do so is to convert some other form of energy present in Nature (wind energy, hydraulic energy...) into useful work.

Thermal energy played a very important part in the industrial revolution which led to present-day society. In the following sections we will deal with its transformation into work.

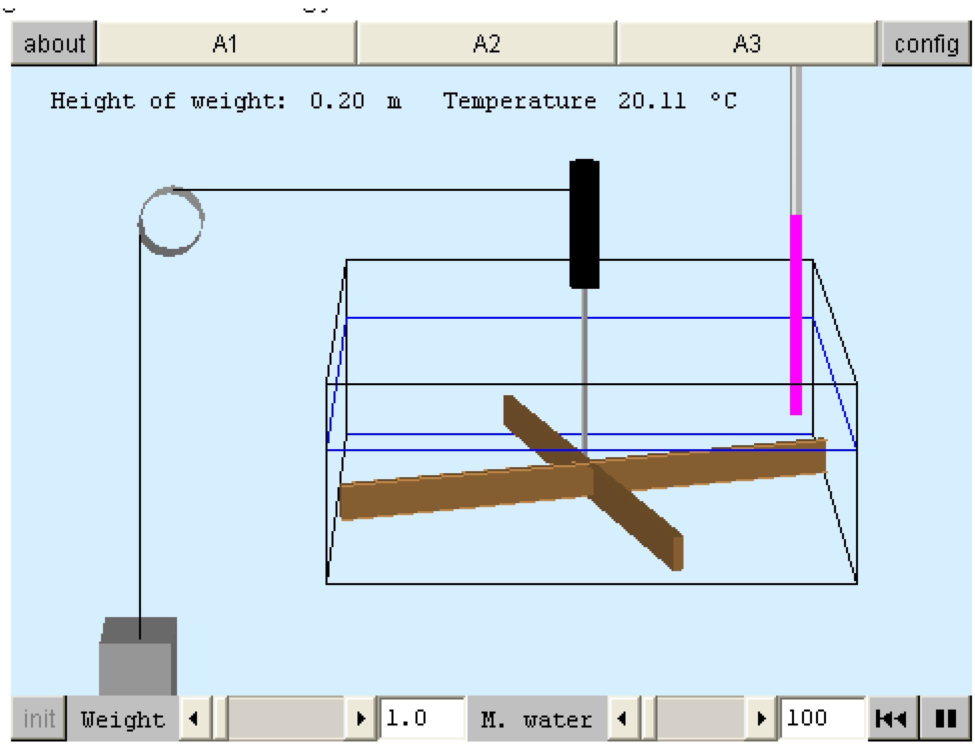
2.1 Joule's experiment

When steam comes out of a pressure cooker, its energy is able to turn the valve. Part of the heat we have supplied to the water is converted into mechanical work. In the same way we know that if we rub two objects together, a form of mechanical work, we produce heat.

Thus, ***mechanical work and heat can be converted into each other***. What is the conversion relation? The famous scientist J. Joule designed an experiment which enabled him to convert mechanical energy into thermal energy under controlled conditions to measure the equivalence between both forms of energy.

In the following visual, we simulate Joule's experiment in a very simplified way.

The weight has a form of energy which can be converted into heat.



A1: What is the name and value of the energy of the suspended weight? Turn on the machine and explain the transformations of energy produced.

A2: Remember that a calorie is the heat necessary to increase the temperature of a gram of water by 1ºC. Calculate, for the greatest weight, the mechanical energy lost, the heat gained by the water and the relation between joules and calories.

A3: Do the following calculation and check it with the visual: What weight would you need to suspend to increase the temperature of 200 grams of water by 0.5ºC?

2.2 The first law

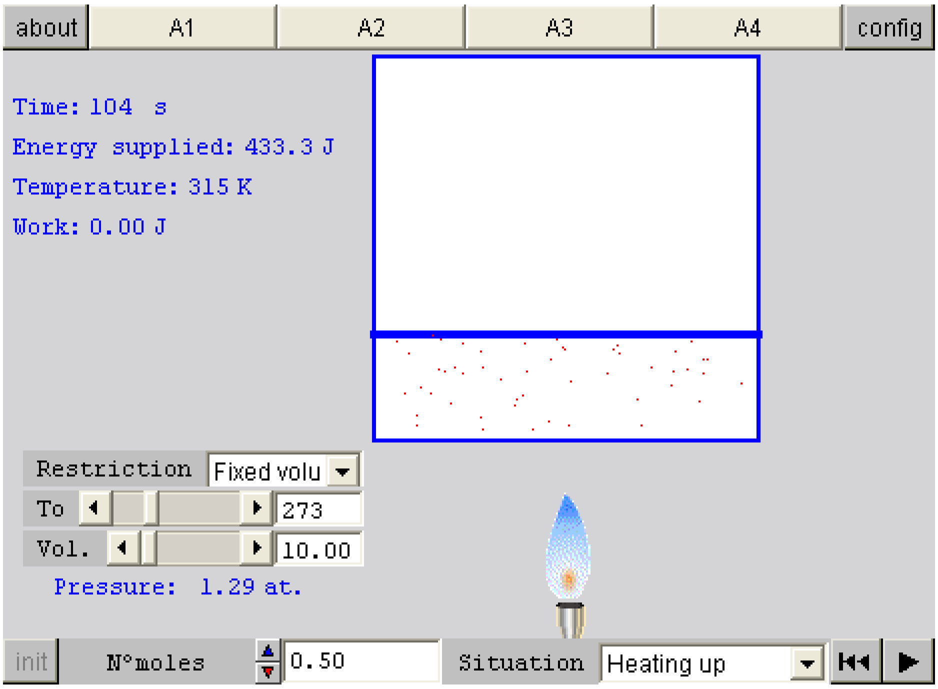
When we heat a pressure cooker, the heat we supply to the water is used to increase the temperature of the water, to evaporate part of the liquid and to produce mechanical work on the safety valve as the steam escapes through it. The heat we started with has been distributed into different forms of energy.

The first law of thermodynamics establishes how this distribution is made.

In the following visual we will try to rediscover this first law by exploring a very simple system: a gas is contained in a receptacle whose walls absorb a negligible amount of heat.

The lid of the receptacle can slide up and down depending on the pressure of the gas, unless we fix it purposely to maintain the volume constant.

The dots simulate molecules. We represent 0.1 moles per 10 molecules (we all know that in reality there are many more).



A1: Select the fixed volume option. Click on play and stop the simulation after approximately 100 seconds. Write down the energy supplied and the pressure reached. Click on play again and note down the values corresponding to 200, 300 and 400 seconds. What relation can you see between the energy supplied and the increase in temperature? How about between temperature and pressure? Explain the results in a reasonable way.

A2: Select the fixed pressure option and repeat the data collection done in the previous exercise. Compare the temperature reached in each case. What is the difference due to? The first law of thermodynamics precisely explains the result of this exercise. How would you state it?

A3: It is common to calculate the specific heat of a gas per mole, instead of calculating it per gram. With the data from the previous exercises, calculate the specific heat of the gas in the visual at a constant volume and at a constant pressure.

A4: Do the following calculations and check them with the visual: How long would it take to increase the temperature of a mole of this gas from 10 to 273 K at a constant volume? How about at a constant pressure? What work would be done in the latter case?

2.3 Conclusions about the relation between heat and mechanical energy

The heat necessary for a gram of water to increase its temperature by one degree Celsius is called a calorie. Joule's experiment establishes that one calorie is equal to 4.18 J.

The first law of thermodynamics could be expressed as follows:

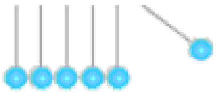
Q = W + AU

Q is the heat gained or lost by the system, W is the work done and AU is the variation in the internal energy of the system.

When we heat or cool a system with a constant volume no work is done and the heat received or lost is translated into an increase or decrease in its temperature.

When we heat a system with a constant pressure work is done: W= P·AV where P is the pressure and AV is the variation in the volume of the system.

3.1 Perpetual motion



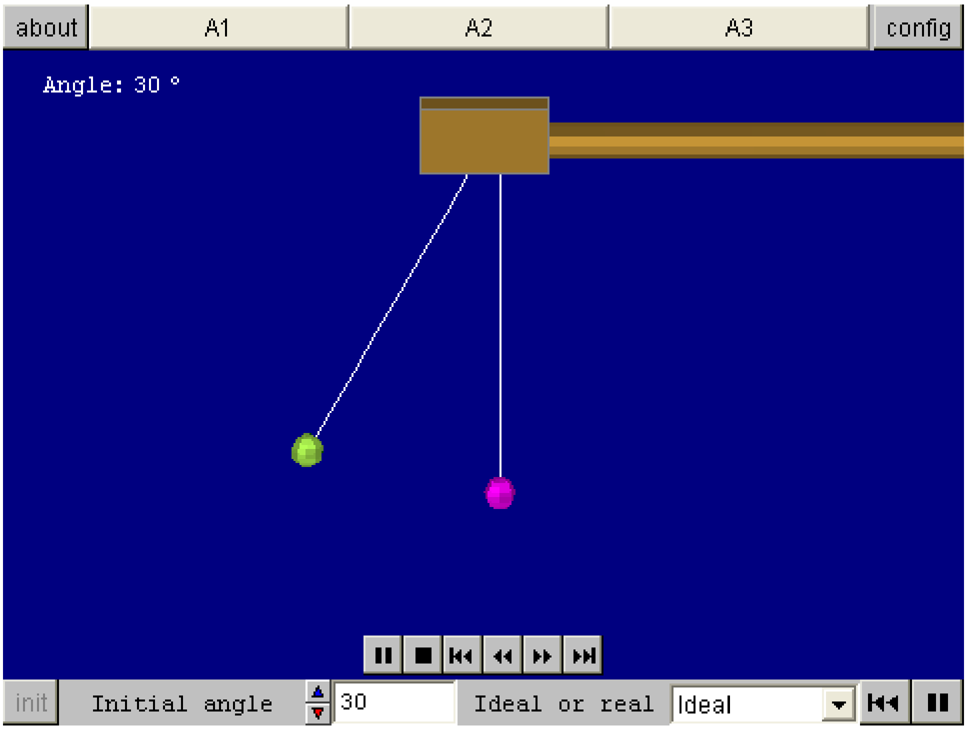
We are sure you are familiar with the little device shown in the figure. It shows the transformation of potential energy into kinetic energy and vice versa. Can you identify these transformations?

A long cherished aspiration of mankind, which has given rise to the design of numerous devices, has in fact been to achieve a device which would convert some form of energy (electrical, thermal etc.) into kinetic energy, which in turn would be converted back into its earlier form of energy.

In this way we would obtain an endless cycle which we would call **perpetual motion.**

Is perpetual motion possible?

To be able to answer this question we will begin by analyzing how the device illustrated above works. You will be able to do this analysis in the following visual. We have assumed that we are dealing with only two balls of identical mass hanging from strings which are 1 m. long.
A simple model of the so-called perpetual motion



A1: Click on play. What is the energy of the green ball when the movement starts? What is its energy when it collides with the pink ball? What does the latter ball's energy transform into after the collision? When would the system stop working?

A2: Repeat the experiment for different angles, always in the ideal mode. Can you see a relation between the angle and the kinetic energy acquired by the balls? What can you see regarding the angle reached by the pink ball?

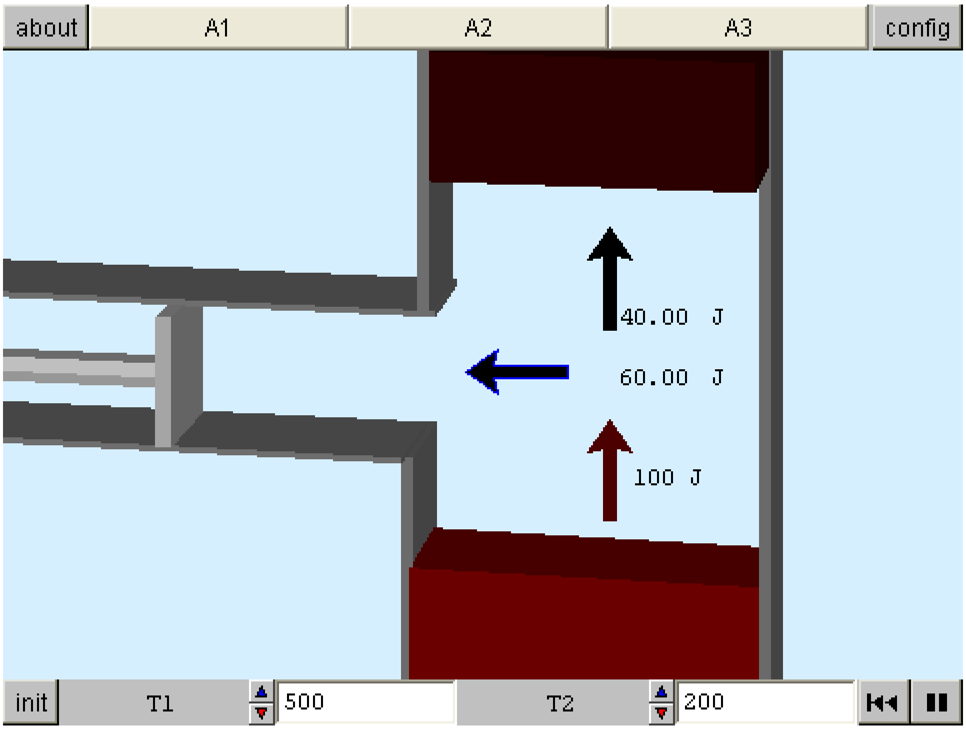
A3: Select the real mode and repeat the experiment for different initial angles. What happens after each collision? What is this due to? Does the movement continue indefinitely?

3.2 The second law of thermodynamics

In the previous visual you will have noticed how it is not possible to achieve a perfect cycle when converting between two forms of energy. There is always some loss during the cycle.
Although we have only seen a very simple example, in all the ingenious devices for perpetual motion invented by man the same thing has happened. There have even been cases or notorious swindlers who invented false perpetual motion machines (one of them even managed to deceive the Czar Peter the Great, the person portrayed in the monument).

Finally the so-called second law of thermodynamics was accepted, which we could express as follows: It is not possible to achieve perpetual motion based on continuous reciprocal conversion between two forms of energy.
As in many present-day machines, heat is used to generate movement, in the following visual we examine what form the second law presents for machines which work with energy produced by a heat source.

General sketch of the second law of thermodynamics.



A1: Click on play. Observe that the system absorbs heat from a hot source and transmits part of it to a cooler source. Another part of the heat is converted into mechanical energy used to move the piston. You can now see the obvious result of the second law of thermodynamics.

A2: The efficiency of the system is determined by the proportion of energy extracted from the hot source and converted into mechanical work. Calculate its value for different temperatures. How does the efficiency change when the temperatures both increase? Are there any values for which the efficiency is zero? How would you express the efficiency in terms of the temperatures mathematically?

A3: Do the following calculations and check them with the visual: In this case the hot source is in the range of 500 to 1000 K and the cold source is in the range of 200 to 500 K. What is the maximum efficiency that we can expect? What temperatures would give us an efficiency of 50%?

3.3 Conclusions about the second law of thermodynamics

The second law can be expressed in several alternative ways:

It is not possible to construct a continually moving object based on the cyclical conversion between two forms of energy. In some part of this cycle energy will inevitably be lost, preferably in the form of heat.

A heat engine extracts heat from a heated source. A part of this energy is converted into mechanical energy and another is released to a cooler source. In a more summarized form:$Q1=W+Q2$.

Where Q1 is the heat extracted from the heated source, Q2 is that released to the cooler source and W the work done.

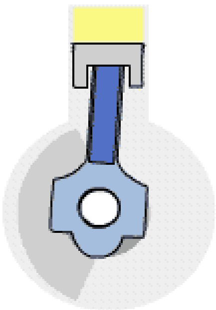
The efficiency of the engine will be $R=W/Q1$ The maximum efficiency of a heat engine would be:

$$R=\frac{T1-T2}{T1}$$

where T1 is the temperature of the heated source and T2 is the temperature of the cooler source.

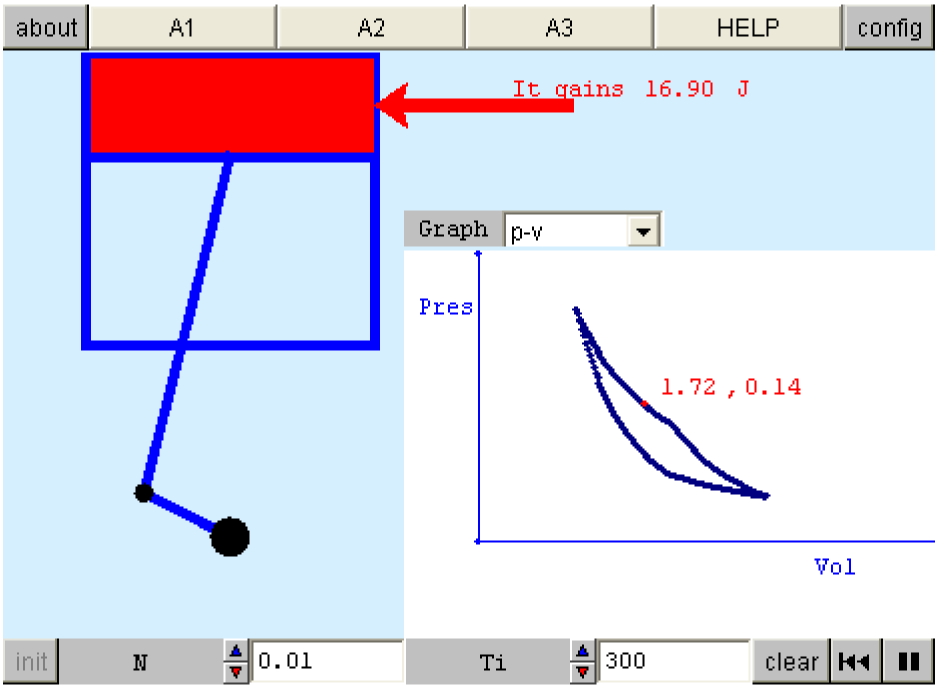
4.1 Carnot's ideal engine

Knowing the limits imposed by thermodynamics, the engineer Carnot designed the model of an engine which could comply with them...
It is a theoretical model, not a real one, but we can already see in it the fundamental characteristics of real heat engines:
The system is based on the phenomena of the expansion and contraction of gases through heat gain and loss.
The work of expanding and contracting the gases can be easily converted into the typical circular movement of the majority of engines.



The piston, the mechanism we see in the figure, is responsible for converting its displacement into a circular movement which can subsequently be converted to displace a vehicle, move a crane, a robot, etc.

The following visual will help you understand Carnot’s design.



A1: Observe the cycle changing the type of graph. How many phases can you see? In which of these is heat gained or lost? How does the temperature evolve in these cases?

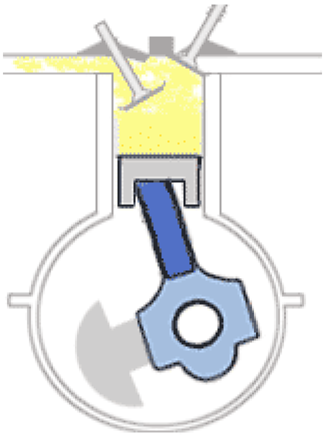
A2: To calculate the efficiency of the machine you should take into account that only the heat that is not given to the cooler source is considered to perform useful work. What percentage of the heat received in the first phase does this work represent? This value is the efficiency of the Carnot cycle.

A3: Change the number of moles of the gas in the process. How is the efficiency altered? What if the initial temperature is altered?

HELP: The play control runs the animation of the Carnot cycle. In order to understand the phases, you can select among the pressure vs. volume, pressure vs. temperature and volume vs. temperature graphs. The pressure is measured in atmospheres, the volume is measured in litres and the temperature is measured in Kelvin. You can change the number of moles of gas in the piston and its initial temperature.

4.2 A real engine

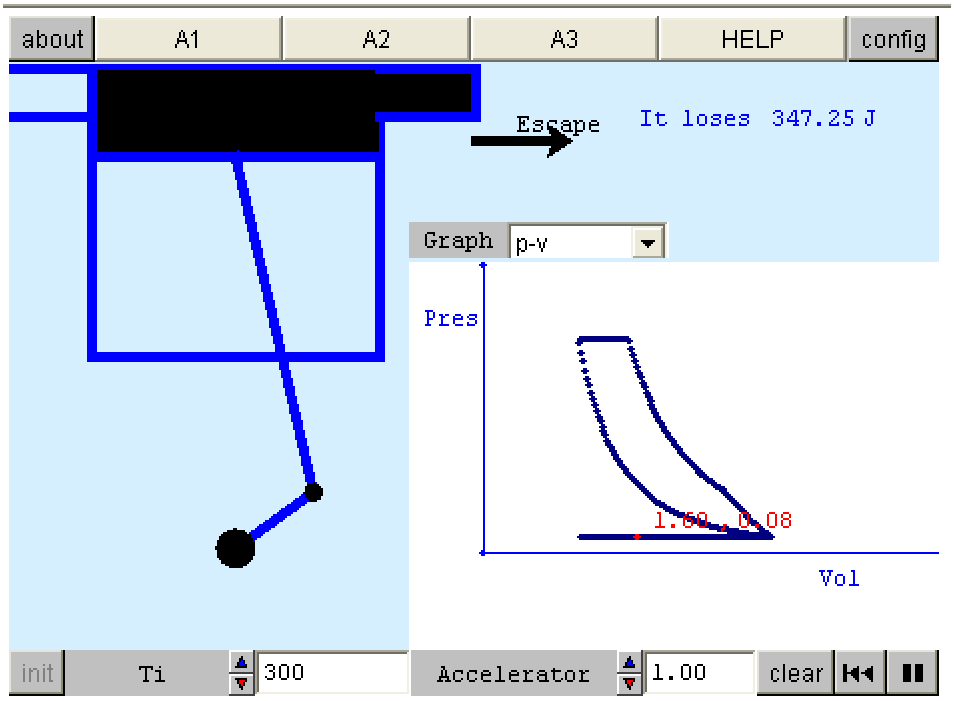
In real combustion engines, energy is extracted by burning some fuel, which has previously been injected into the cylinder, finely pulverized and mixed with oxygen. Then the combustible mixture is compressed and ignited to explode.



The energy from this combustion moves the piston in several phases as seen in the figure on the left.

In the following visual we study the modern combustion engine, in an approximate fashion, and we try to explain these phases.

A real internal combustion engine with explanatory diagrams.



A1: Observe the cycle changing the graphs. How many phases can you see? In which of them is heat gained or lost? How does the temperature evolve in these cases?

A2: To calculate the efficiency you should take into account that only the heat not transferred to the cooler source is considered to produce useful work. What percentage of this heat gained in the first phase does this work represent? This value is the efficiency of the motor.

A3: Change the acceleration of the motor. How is the efficiency altered? What if the initial temperature is changed?

HELP: The play control starts the motor. In order to understand the phases you can choose among the pressure vs. volume, pressure vs. temperature and volume vs. temperature graphs. You can accelerate the motor (by increasing the amount of fuel) and its initial temperature.

4.3 Conclusions about heat engines

As a theoretical model of an engine, **the Carnot cycle** is based on a gas being put through four operations: expansion at a constant pressure, receiving heat from a hot source; adiabatic expansion, where heat is neither gained nor lost, contraction at a constant pressure, giving out heat to a cooler source, adiabatic contraction.

The **real combustion engine** is based on the injection of a pulverized combustible mixture, its compression and explosion, ending with the compression and expulsion of the exhaust gases.

In both cases, the movement of the piston transforms the expansion and the contraction of the gases into a circular movement which can be employed for mechanical uses.

EVALUATION

Choose the right answer to each question.

What do you know about heat engines and machines?

1 What does the first law of thermodynamics say?
When a body absorbs heat,...

☐ it is all converted into work.

- [ ] It is all emitted to the exterior again.
- [ ] this heat can be transformed partly in work and partly into internal energy of the system.
- [ ] It is always converted into an increase in internal energy.

2 An artifact like the lever

- [ ] Increases the work done to lift a body
- [ ] Reduces the work that you need to carry out a task
- [ ] Reduces the effort that you need to carry out a task
- [ ] Reduces the work done to lift a body

3 The second law of thermodynamics means that in practice...

- [ ] the efficiency of an engine depends only on the temperature of the hot source
- [ ] it is not possible to make an engine with an efficiency of 100%.
- [ ] the efficiency of an engine depends only on the temperature of the cool source
- [ ] it is possible to make an engine with an efficiency of 100%.

4 In Carnot´s ideal engine

Carnot´s ideal engine

- [ ] the work done is equal to the heat emitted to the cool source.
- [ ] heat is absorbed during two of the four phases and it is emitted in the other two.
- [ ] the work done is equal to the heat absorbed.
- [ ] heat is absorbed in one of the four phases and it is emitted in another

5 Artifacts like the windmill and the water wheel

- [ ] produce a continuous movement without consuming energy
- [ ] Have an efficiency of 100%, that is, they transform all the energy

into work

☐ can only work if some combustible like petrol is supplied

☐ Transform some type of natural energy into the kinetic energy of the machine

Do you know how Carnot´s engine works?

Select the part of the process corresponding to each phase

First phase

The gas contracts in an adiabatic process (without absorbing or emitting heat)
The gas expands, absorbing heat at a constant temperature
The gas consumed leaves the machine
The gas contracts at a constant temperature, emitting heat
The gas expands in an adiabatic process (without absorbing or emitting heat)

Second phase

The gas contracts in an adiabatic process (without absorbing or emitting heat)
The gas expands, absorbing heat at a constant temperature
The gas consumed leaves the machine
The gas contracts at a constant temperature, emitting heat
The gas expands in an adiabatic process (without absorbing or emitting heat)

Third phase

The gas contracts in an adiabatic process (without absorbing or emitting heat)
The gas expands, absorbing heat at a constant temperature
The gas consumed leaves the machine
The gas contracts at a constant temperature, emitting heat
The gas expands in an adiabatic process (without absorbing or emitting heat)

Fourth phase

The gas contracts in an adiabatic process (without absorbing or emitting heat)
The gas expands, absorbing heat at a constant temperature
The gas consumed leaves the machine
The gas contracts at a constant temperature, emitting heat
The gas expands in an adiabatic process (without absorbing or emitting heat)

Write a general summary

Simple machines like levers save us ____, but not ____.

Artifacts like windmills and hydraulic turbines replace human ____ by transforming a natural form of ____ into mechanical energy.

Heat engines work because they receive energy in the form of ____ from a ____ source (as, for example the ____ of petrol) and they transform part of it into mechanical ____.

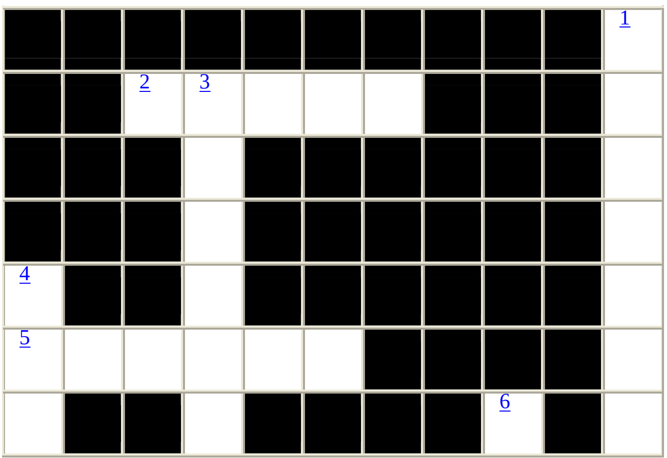
It is impossible to achieve 100% ____, because it is forbidden by the ____ law of ____.

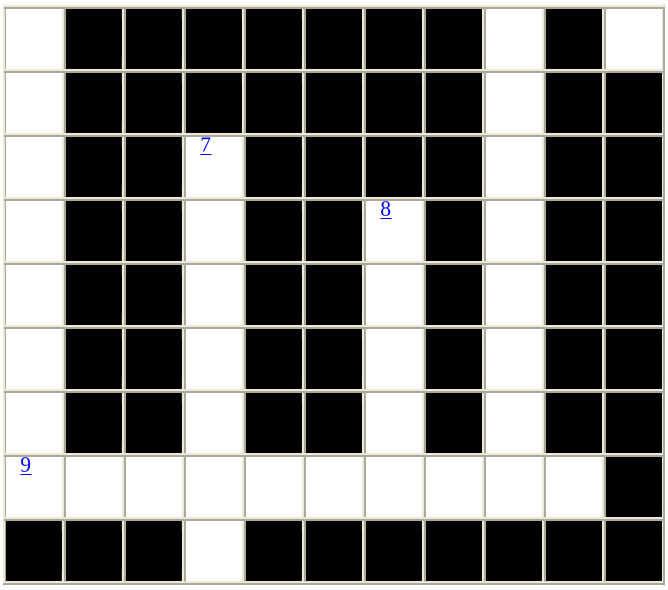
The maximum efficiency that we can expect is determined by the ____ of the source the engine receives energy from and the temperature of the source it emmits ____ to.

Complete the crossword and verify the result with the check button

Work and heat

Crossword

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